Heavy Ion Physics at the LHC with the ATLAS Detector

P Steinberg, on behalf of the ATLAS Collaboration

Brookhaven National Laboratory, Upton, NY 11973

E-mail: peter.steinberg@bnl.gov

Abstract. The ATLAS detector at CERN will provide a high-resolution longitudinally- segmented calorimeter and precision tracking for the upcoming study of heavy ion collisions at the LHC ($\sqrt{s_{NN}} = 5520$ GeV). The calorimeter covers $|\eta| < 5$ with both electromagnetic and hadronic sections, while the inner detector spectrometer covers $|\eta| < 2.5$. ATLAS will study a full range of observables necessary to characterize the hot and dense matter formed at the LHC. Global measurements (particle multiplicities, collective flow) will provide access into its thermodynamic and hydrodynamic properties. Measuring complete jets out to 100's of GeV will allow detailed studies of energy loss and its effect on jets. Quarkonia will provide a handle on deconfinement mechanisms. ATLAS will also study the structure of the nucleon and nucleus using forward physics probes and ultraperipheral collisions, both enabled by segmented Zero Degree Calorimeters.

1. Introduction: Heavy Ion Physics at the LHC

Heavy ion physics at the LHC is the next natural step in the evolution of the understanding of QCD. This can be seen most clearly when one considers the dynamical evolution of a heavy ion collision. The study of particle multiplicities and monojets give insight into high density QCD and the parton structure of the nucleus via models based on parton saturation, such as the color glass condensate[1]. Hard processes probe the very earliest phase of the collision process via the production of jets, photons, and heavy quark states from parton-parton interactions [2]. Through the use of these calibrated probes, one can study their modification in nuclear collisions and thus learn about QCD in medium as well as the medium itself [3]. By the study of particle yields in η, ϕ and p_T, both inclusive and identified, one can make connections to hydrodynamics (both ideal and not) and probe the equation of state which encodes the relevant microscopic degrees of freedom [4]. Finally, the study of integrated yields and the comparison of different hadron species and their decays gives a handle on the thermal and statistical properties of the system [5].

The suite of collision systems (p+p, A+A, p+A) and detectors (ALICE, ATLAS, and CMS) at the LHC are ideally suited to address all of the above theoretical questions via precise experimental measurements using phenomenological tools developed in the
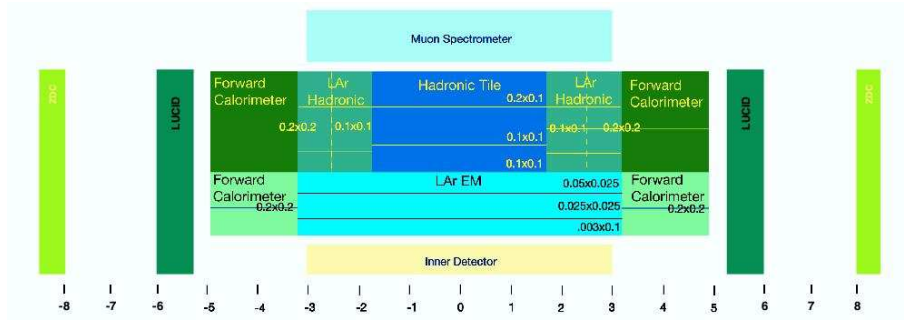
Figure 1. ATLAS acceptance in pseudorapidity. All detectors have complete azimuthal coverage.

context of RHIC collisions [2, 6]. Here we discuss the progress of the ATLAS heavy ion effort to ready itself for Pb+Pb running in late 2008 or early 2009. Previous progress in preparations for ATLAS running have been reported in Refs. [7, 8, 9, 10, 11] and in the Letter of Intent [12]. ‡
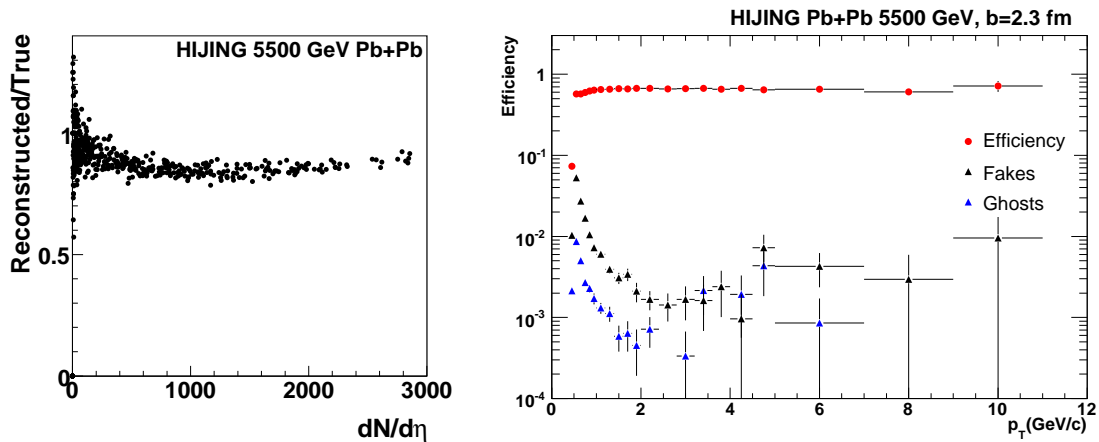
2. ATLAS Detector

The ATLAS detector is a powerful tool for studying the high multiplicity of particles that emerge from the collision of protons and nuclei [13, 14]. A particular strength of the ATLAS detector is the hermetic liquid argon (LAr) electromagnetic (EM) calorimeter, which provides excellent energy and position information on electrons and photons via its longitudinally-segmented towers [15]. Of course, there is also a sophisticated inner tracking system for reconstructing charged tracks and a large volume muon tracking system.

Like many modern collider detectors, ATLAS has hermetic azimuthal coverage over a wide range in pseudorapidity. The inner tracking system covers $|\eta| < 2.5$ with silicon pixels, silicon strips (SCT), and a straw-tube transition-radiation tracker (TRT). The electromagnetic calorimeter covers $|\eta| < 3$ with angular resolution depending on the layer ($\Delta\eta \times \Delta\phi = 0.003 \times 0.1, 0.025 \times 0.025, 0.05 \times 0.025$). The barrel hadronic tile calorimeter covers ($|\eta| < 1.8$) with towers of 0.1×0.1. In the forward direction, the hadronic forward calorimeter has cells up to 0.2×0.2, and a forward LAr calorimeter covers up to $\eta = 5$ with cells of 0.2×0.2.

Additional detectors will extend the ATLAS acceptance farther into the forward region. The LUCID gas Cerenkov detector [16] detects primary charged particle from $5.3 < |\eta| < 6$. While it will be primarily purposed for luminosity monitoring, it should

‡ **Note on Figures:** Unless otherwise noted, the figures shown here were based on studies using modified versions of ATLAS production software. Thus, they should be considered "ATLAS preliminary". For completeness, we list the version of Athena software used for each figure: Figure 2(left) used 12.0.31 with a new tracking algorithm while Figure 2(right) and Figure 3 used 12.0.3. Figures 4-6 used 11.0.41 and special jet algorithms. Figure 7(right) was produced with an unmodified 11.0.3.

Figure 2. (left) Reconstruction of tracklets in the ATLAS pixel detectors. (right) Tracking reconstruction efficiency, ghost rate, and fake rate in central HIJING events.

also provide a measure of forward particle yields with a readout system that can resolve multiple particles per tube. More importantly for heavy ion physics is the Zero Degree Calorimeter (ZDC) being designed and built especially for ATLAS by a consortium of US groups [17]. This detector will be able to detect forward neutron spectator fragments, which serves as both a high-purity event trigger as well as an estimator for the "centrality" of the collision (related directly to the impact parameter). However, its highly-segmented front EM section will also be able to measure the angle of neutral clusters. This allows the reconstruction of neutral decays like π^0 and η, which will be discussed below.

3. Global Dynamics

The most pressing issue for the early days at the LHC is to establish the global features of heavy ion collisions. This involves the estimation of the inclusive charged-particle yield, both integrated and as a function of pseudorapidity, to get a handle on the initial-state entropy production which controls the hydrodynamic evolution as well as jet quenching [18]. It also entails studying the elliptic flow for inclusive particles as a function of centrality, p_T and pseudorapidity [19]. One of the major questions for the LHC heavy ion program is whether the presumed "hydro limit" has really been reached in RHIC collisions, or if the magnitude of elliptic flow scaled by the eccentricity (v_2/ϵ) will continue to increase with particle yield.

Estimating the particle density can be done in a variety of ways. Even before the tracking system is fully commissioned, a reasonably-aligned pixel detector can be used to measure particle yields by the "tracklet" technique pioneered at RHIC by the PHOBOS experiment [20]. This technique involves matching the angles of two pixel space points with the estimated event vertex measured using the rest of the inner detector. While it is not as robust as the full tracking procedure, it has a lower intrinsic p_T cutoff and
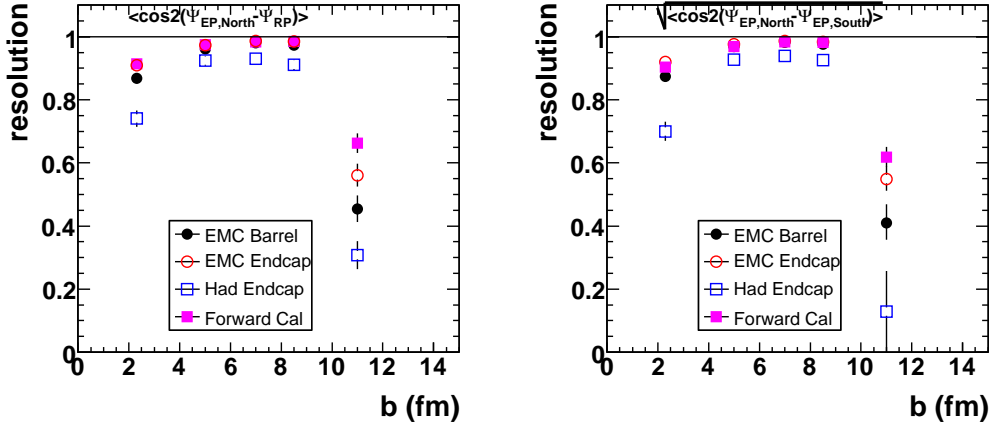
Figure 3. Two calculations of reaction plane resolution in ATLAS, relative to the true reaction plane (left) and between symmetric subevents (right). See text for definitions of these quantities. Results are shown for different calorimeter subdetectors, which cover different pseudorapidity regions (see Fig. 1).

thus offers quick access to the full yield. Initial studies of tracklets with full simulations, shown in the left panel of Fig. 2, show a good efficiency which is constant over a wide range of multiplicities emitted in $|\eta| < 1$. Of course the full inner detector will be indispensible for estimating particle yields and spectra. The performance of early studies of the full tracking algorithm in a heavy ion environment is shown in the right panel of Fig. 2. For central ($b = 2.3$ fm) HIJING events, we find an approximately constant efficiency of $\sim 70\%$ over a broad range in p_T and low fake and ghost rates.

Estimating elliptic flow involves the calculation of the Fourier components of the measured angular distribution relative to the "reaction plane" (the angle Ψ_{RP} seen by the neutron spectators) or "event plane" (the angle Ψ_{EP} seen by the emitted particles themselves) [21]. The parameter v_2 is defined via the expansion $dN/d\phi \propto 1 + 2v_2 \cos[2(\phi - \Psi)]$ where $\Psi = \Psi_R$ or Ψ_E, and is estimated by calculating $v_2 = \langle\cos[2(\phi - \Psi)]\rangle$ from experimental data.

The key figure of merit which controls the quality of the measurement is the reaction plane resolution which is used to correct the experimental data. This can be estimated in an ideal case by the expression $\langle\cos(\Psi_{EP} - \Psi_{RP})\rangle$. In a real measurement, it is typically assumed that the full event sees the same reaction plane and the formula $\sqrt{\langle\cos[2(\Psi_{EP,N} - \Psi_{EP,S})]\rangle}$ is used to estimate the reaction plane resolution by the measurement of two symmetric subevents, one in the forward hemiphere and the other in the backward hemisphere. Fig. 3 shows the ideal and subevent reaction plane resolution as a function of impact parameter and subdetector, each of which cover a different pseudorapidity region. The resolutions are typically near 1 for most of the inelastic cross section. Even for the most challenging environments, e.g. peripheral collisions with low multiplicity and central collisions with a low v_2 signal, they are always above 0.3. These high resolutions provide a major advance over RHIC measurements which
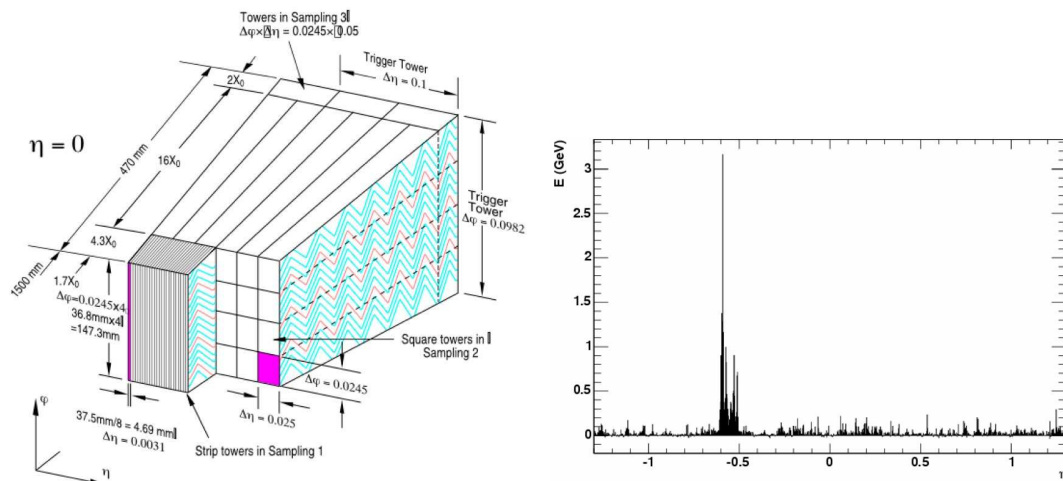
Figure 4. (left) Schematic of the ATLAS EMCAL longitudinal segmentation. (right) Signals in the first EMCAL layer strips, showing a photon amidst uncorrelated HIJING background.

had reaction plane resolutions typically *below* 0.5 [22, 23].

4. Jets

The detailed study of fully-reconstructed jets will be the major contribution of the LHC to the understanding of the strongly-interacting QGP thought to be formed in heavy ion collisions at RHIC. Both the copious production of jets and the experimental acceptance are unprecedented in the study of relativistic heavy ions [2]. The rates of hard processes in $p + p$ and $A + A$ collisions will increase dramatically relative to RHIC energies. Of course, so will the yields of uncorrelated soft particles, which may well suffer enormous fluctuations if copious minijet production indeed dominates the bulk particle production. Thus, it is essential to have a calorimeter with a large acceptance in η and ϕ with excellent energy and position resolution, to contain full jet, dijet, γ-jet and Z-jet events. Combining information from the different measurements will provide a good handle on the jet E_T scale (e.g. from γ-jet and Z-jet event) and fragmentation properties.

As mentioned above, the longitudinal segmentation of the ATLAS electromagnetic (EM) calorimeter, illustrated in Fig.4 is unique at the LHC and will be essential for jet physics at the LHC [15]. Detailed simulations have shown that 60% of the total energy (including both charged and hadronic energy) ranges out in the first EMCAL layer. Most of the hadronic component is charged and only leaves MIPS in the first layer. This means that photons, especially those of several GeV and above, are easily observed above the large central HIJING background in the first layer, as shown in Fig. 4. This will dramatically enhance ATLAS's ability to make direct photon measurements by being able to reject even close decay photon pairs [24].
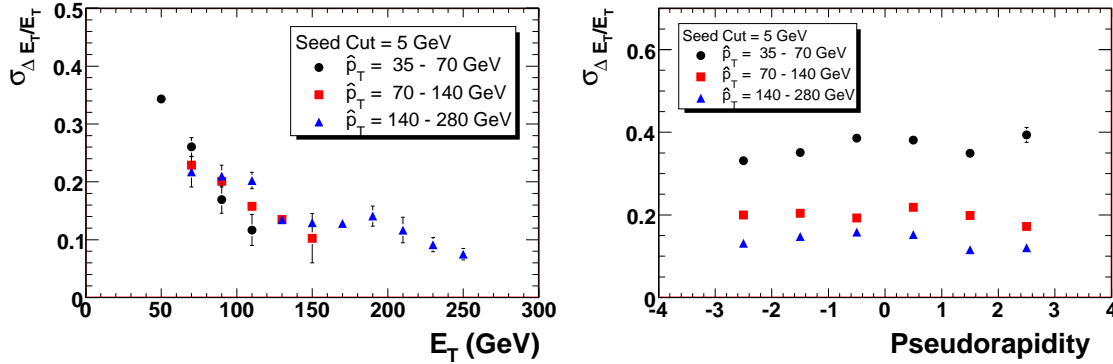
Figure 5. Energy resolution for jets in the ATLAS acceptance, as a function of jet E_T and η.

In order to study the ability of ATLAS to identify and reconstruct jets, e.g. generated by PYTHIA, they are embedded into heavy ion events. From these samples, various reconstruction procedures can be tested and evaluated. One procedure involves estimating the background by excluding jet candidates and averaging the energy in the calorimeters within a chosen tower size. This average energy is subtracted and then the standard ATLAS jet reconstruction algorithms are run on the modified towers. This allows heavy ion data analysis to take advantage of progress with jet reconstruction algorithms and calibration. The current results, applying the subtraction technique and the standard ATLAS jet reconstruction algorithms down to 50 GeV, are shown in Fig.5 for jets ranging from $E_T = 50 - 300$ GeV and resolutions range from $\sim 25\%$ at the lowest energies considered to $10 - 12\%$ at higher energies. The resolution is currently independent of η, as seen in Fig. 5 for $|\eta| < 2.5$.

Another technique currently under intense development is one applying the "Fast k_T" algorithm [25] directly to heavy ion data without a separate subtraction step. In general, k_T algorithms reconstruct jets backwards along the fragmentation chain by combining particles that minimize $d_{ij} = \min(k_{iT}, k_{jT})R^2$ (where $R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$) which essentially encodes the $1/k_T^2$ probabilities of parton splitting. While these algorithms are typically $O(N^3)$ (where N is the number of tracks or calorimeter clusters), Cacciari and Salam have used the technique of Voronoi diagrams to reduce the problem to $O(N \log N)$. This allows the algorithm to be run quickly even in central heavy ion events. Early results are shown in Fig. 6. One can set a maximum radius for particles to be clustered, e.g. $R_{max} = 0.4$ which groups the towers into many (e.g. 10's) of jet candidates. These candidates can be characterized by various properties, e.g. maximum tower energy and average cell energy, as illustrated for a single event in the left panel of Fig. 6. The ratio of these quantities for a single event's jet candidates is shown as a function of pseudorapidity in Fig. 6, where it is observed that jets are easily distinguished from the rest of the background on an event-by-event basis, and without a separate background-subtraction step.
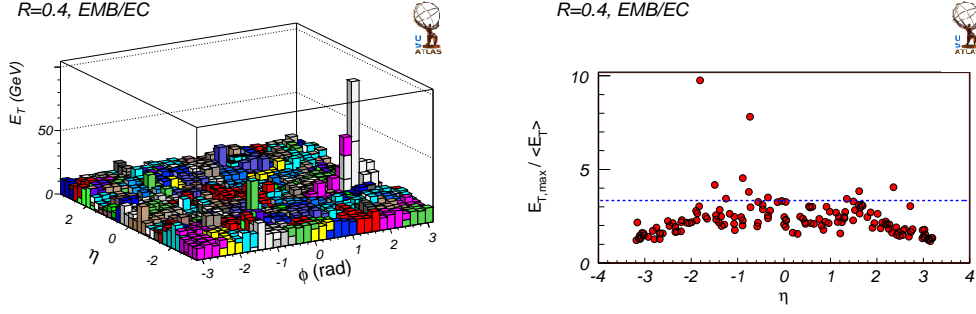
Figure 6. Extraction of jets from ATLAS calorimeters using the "Fast k_T" algorithm.
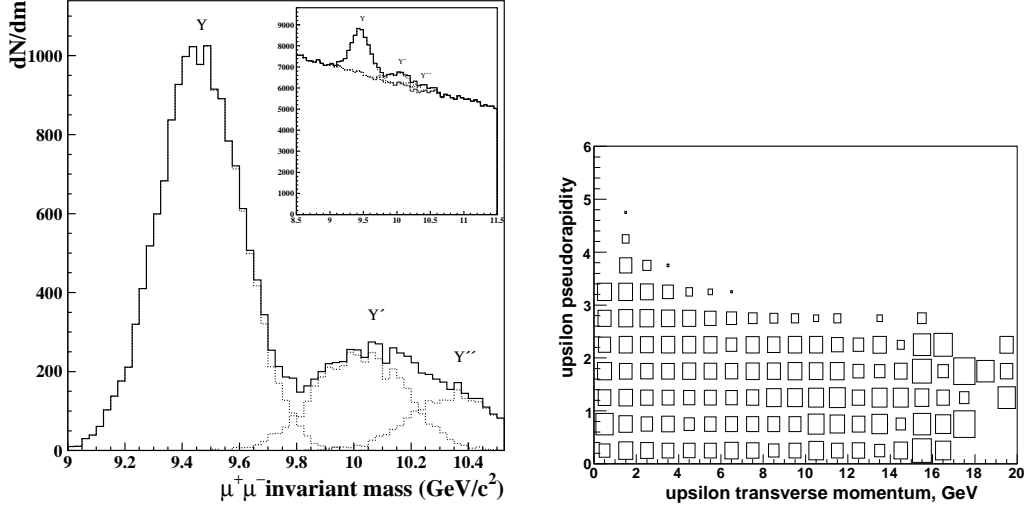

Figure 7. (left) Reconstruction of upsilons within the ATLAS muon spectrometer. (right) Acceptance $\times$ efficiency for upsilons as a function of pseudorapidity (η) and transverse momentum (p_T).

5. Quarkonia

The suppression of J/Ψ's produced in heavy ion collisions has become a major question arising from recent RHIC data. When cast as R_{AA}, it is found that the suppression slightly forward of mid-rapidity is quite similar in data from the SPS ($\sqrt{s_{NN}} = 17.3$ GeV, and RHIC ($\sqrt{s_{NN}} = 200$ GeV) [26]. These two energies are an order of magnitude different, with particle densities different by a factor of two, making the similarity in the data quite puzzling. The LHC will increase $\sqrt{s_{NN}}$ by another factor of 27, which should shed some light on the situation regardless whether the suppression patterns remain energy independent or undergo a dramatic change.

The ATLAS muon spectrometer is a high precision tracker covering $|\eta| < 2.5$ with full azimuth. While it has unprecedented rapidity coverage in heavy ion collisions, its design is optimized for very high energy muons. Thus, while it can measure muons of order 1 TeV, the material budget of the inner detector and calorimeters make it difficult
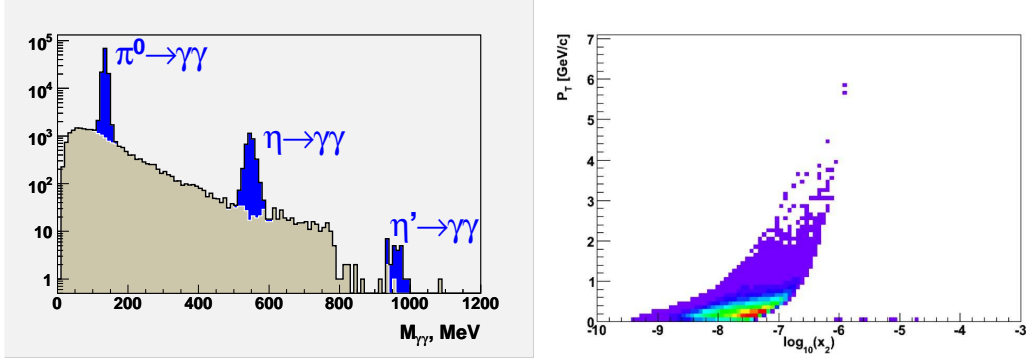
Figure 8. (left) Reconstruction of π^0 and η particles via 2-photon decay into the ATLAS ZDC. (right) Acceptance of ATLAS ZDC for π^0's in p_T vs. x_2.

to reconstruct muons below $p_T = 3$ GeV/c. This imposes minimum p_T cuts on J/Ψ and Υ reconstruction since each muon needs to have several GeV.

The left panel of Fig. 7 shows an ATLAS reconstruction of upsilon mesons reconstructed in a high statistics sample of $p + p$ collisions. The mass resolution at present is $\sigma_{M_\Upsilon} \sim 120 MeV/c^2$ for $|\eta| < 1$, which is only slightly affected by the presence of an uncorrelated heavy ion background. The right panel of Fig. 7 shows the ATLAS acceptance for Upsilons as a function of pseudorapidity and transverse momentum. This figure shows a broad Υ acceptance that goes beyond the nominal spectrometer resolution, stemming from the dimuon decay kinematics, and out to very high p_T. ATLAS will be sensitive to quarkonia states over a wide kinematic range, and will thus probe various aspects of deconfinement dynamics.

6. Low x Physics

The ATLAS ZDCs will be primarily used for centrality selection in A+A as well as the study of ultraperipheral collisions (which will explore similar physics as next-generation electron ion colliders) [27]. However, their ability to reconstruct far-forward π^0's in $p+p$ collisions [17], shown in Fig. 8, gives them particular utility in addressing low x physics. Via the kinematic relations typical for CGC physics, $x_2 \sim (p_T/\sqrt{s})e^{-y}$ (where p_T and y are the transverse momentum and rapidity of the detected π^0), Fig.8 shows the effective range in x_2 and p_T reached for π^0's reconstructed in the ZDC. By probing x_2 down to $10^{-6} - 10^{-8}$ at moderate p_T, even $p + p$ collisions will become interesting laboratories to study universal features of hadronic wave functions [1].

7. Conclusion

In conclusion, ATLAS is preparing intensely for heavy ion data at the LHC in 2008 and beyond. Studies shown in this work include bulk observables in p+p and A+A, inclusive jets in p+p and A+A, quarkonia reconstruction, and early steps towards low-x physics

and ultraperipheral collisions. Of course, important work remains to be done on many tasks. New collaborators are always welcome, to work on software, analysis, physics and trigger issues!

Acknowledgments

References

[1] Iancu E and Venugopalan R 2003 arXiv:hep-ph/0303204.
[2] Accardi A *et al.* 2003 arXiv:hep-ph/0310274.
[3] Adler S S *et al.* 2006 arXiv:nucl-ex/0611006.
[4] Huovinen P and Ruuskanen P V 2006 arXiv:nucl-th/0605008.
[5] Braun-Munzinger P, Cleymans J, Oeschler H and Redlich K 2002 *Nucl. Phys.* A **697** 902
[6] Wiedemann U A 2006 *AIP Conf. Proc.* **842** 11
[7] Rosselet L 2005 *Czech. J. Phys.* **55** B343
[8] White S N 2005 arXiv:nucl-ex/0505020
[9] Takai H 2004 *Eur. Phys. J.* C **34** S307
[10] Takai H 2004 *J. Phys.* G **30** S1105
[11] Nevski P 2004 *Eur. Phys. J.* C **33** S612
[12] "Heavy Ion Physics with the ATLAS Detector" 2004 Letter of Intent, CERN/LHCC 2004-009.
[13] "ATLAS: Detector and physics performance technical design report. Volume 1," 1999 CERN-LHCC-99-14
[14] "ATLAS detector and physics performance. Technical design report. Vol. 2," 1999 CERN-LHCC-99-15
[15] "ATLAS liquid argon calorimeter: Technical design report," 1996 CERN-LHCC-96-41
[16] Pinfold J 2005 "Plans for the very forward region of ATLAS: The lucid luminosity monitor," *Prepared for 9th ICATPP Conference on Astroparticle, Particle, Space Physics, Detectors and Medical Physics Applications, Villa Erba, Como, Italy, 17-21 Oct 2005*
[17] "Zero Degree Calorimeters for ATLAS" 2007 CERN-LHCC-2007-001
[18] Baier R, Dokshitzer Y L, Mueller A H, Peigne S and Schiff D 1997 *Nucl. Phys.* B **484** 265
[19] Kolb P F and Heinz U W 2003 arXiv:nucl-th/0305084.
[20] Back B B *et al.* 2000 *Phys. Rev. Lett.* **85** 3100
[21] Ackermann K H *et al.* 2001 *Phys. Rev. Lett.* **86** 402
[22] C. Adler *et al.* 2002 *Phys. Rev.* C **66** 034904
[23] Back B B *et al.* 2002 *Phys. Rev. Lett.* **89** 222301
[24] Escalier M *et al.* 2005 ATL-PHYS-PUB-2005-018
[25] Cacciari M and Salam G P 2006 *Phys. Lett.* B **641** 57
[26] Lajoie J 2006 these Proceedings.
[27] Strikman M, Vogt R and White S 2006 *Phys. Rev. Lett.* **96** 082001